NSWCCD-50-TR-2007/044 Induced Forces and Moments of a Tumblehome Hullform (Model 5613) Undergoing Forced Roll in Waves

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Induced Forces and Moments of a Tumblehome Hullform (Model 5613) Undergoing Forced Roll in Waves

by

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Predictions of large amplitude roll motions and capsize events have proven to be difficult and include large uncertainty. A factor that contributes to the difficulty in predictions is a lack of knowledge of resultant forces and moments for large roll angles. The equations currently used by numerical models to predict forces and moments due to roll motion are based on experimental data performed within a small range of roll amplitudes. For this reason, a data set of forces and moments is needed to verify that the model predictions are accurate in the upper ranges. If the predictions are inaccurate for the larger roll angles, a need may exist to develop new models to predict the forces and moments for these larger roll amplitudes.

In 2006, NSWCCD performed an experiment on Model 5613 to obtain the model scale constrained seakeeping results during large amplitude motions in waves, in contrast to the calm water experiments of 2005. Similar to the 2005 experiment, the effects of model speed, roll amplitude, roll frequency, wave height and wave length on the forces and moments were investigated in an effort to develop a database of surge, sway, and heave forces, and roll, pitch and yaw moments as a result of large amplitude forced roll motions in waves. This report will describe the experimental setup and results of the 2006 experiment.

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ABSTRACT

Predictions of large amplitude roll motions and capsize events have proven to be difficult and include large uncertainty. A factor that contributes to the difficulty in predictions is a lack of knowledge of resultant forces and moments for larger roll angles. The equations currently used by numerical models to predict forces and moments due to roll motion are based on experimental data performed within a small range of roll amplitudes. For this reason, a data set of forces and moments is needed to verify that the model predictions are accurate in the upper ranges. If the predictions are inaccurate for the larger roll angles, a need may exist to develop new models to predict the forces and moments for these larger roll amplitudes.

In 2005, the Naval Surface Warfare Center, Carderock Division, (NSWCCD) tested NSWC Model 5613, a tumblehome hullform. The primary objective of that experiment was to obtain model scale constrained seakeeping results to provide information necessary to perform the verification of surge, sway, heave forces and motions, and roll, pitch, and yaw moments and motions acting on a surface combatant hull during large amplitude motions. This experiment generated a database of forces and moments experienced by a surface combatant hull that occurred as a result of large amplitude roll motions extending up through 50°.

In 2006, NSWCCD performed a similar experiment on Model 5613 to augment the 2005 data. The objective for this experiment was to obtain the model scale constrained seakeeping results during large amplitude motions in waves, in contrast to the calm water experiments of 2005. Similar to the 2005 experiment, the effects of model speed, roll amplitude, roll frequency, wave height and wave length on the forces and moments were investigated in an effort to develop a database of surge, sway, and heave forces, and roll, pitch and yaw moments as a result of large amplitude forced roll motions in waves. This report will describe the experimental setup and results of the 2006 experiment.

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ADMINISTRATIVE INFORMATION

The work described in this report was performed by the Maneuvering and Control Division (Code 5600) of the Hydromechanics Department at the Naval Surface Warfare Center, Carderock Division (NSWCCD). This work was funded by contract N0001406WX20710 from the Office of Naval Research, under the direction of Dr. L. Patrick Purtell, work unit numbers 06-1-5600-446-XX, 06-1-5600-457-XX, 06-1-5600-445-XX, and 06-1-5600-458-XX.

INTRODUCTION

A variety of numerical methods currently exist to predict ship motions. Nearly 30 years ago, Ikeda developed a component-based method for the prediction of ship roll damping, a method which is based on both theory and empirical data, and is still widely used today (1, 2, 3, 4, 5, 6). In addition, Matusiak developed a two-stage approach to the determination of large amplitude motions of a rigid ship in waves, which qualitatively agreed with experimental results (7). Gorski discusses the role of Reynolds Averaged Navier-Stokes (RANS) equations in solving seakeeping problems, where he describes an accurate RANS prediction of the roll motion (15°) of a cylinder with forward speed (8). Experiments to study extreme ship motions have been performed at INSEAN (the Italian ship model basin) for surface combatant hulls free to heave and roll in beam seas (9). In addition, Irvine performed a range of free roll decay experiments at the University of Iowa for a surface combatant hull, where motions, forces, and moments were simultaneously measured (10).

The equations currently used by numerical models to predict forces and moments due to roll motion are based on experimental data performed over a small range of roll amplitudes. A data set of forces and moments due to a larger range of roll amplitudes (up to 45°) in waves is necessary to verify that the model predictions were accurate in the upper ranges, and in addition, to develop new methods to predict the forces and moments for these larger roll amplitudes in waves. The data collected by NSWCCD in 2005 (11) was part of this data set. The objective of the 2006 experiment was to obtain the model scale constrained seakeeping results to provide information necessary for numerical model verification of surge, sway, and heave forces and roll, pitch, and yaw moments acting on a surface combatant hull during large amplitude motions and capsize events in waves, including the effects of model speed, roll amplitude, roll frequency, wave height and wave length on the forces and moments.

To accomplish this objective, a modern surface combatant model (λ= 32, Model 5613) with 10° tumblehome sides was towed on Carriage 2 in waves and forced in roll using a motor-driven mechanism through large roll amplitudes of up to 50° to port and starboard while also controlling the roll frequency.

MODEL DESCRIPTION

The model used for this test was the 1/32 scale NSWCCD Model 5613, with interchangeable topsides, including a 10° tumblehome topside, a wall-sided topside, and a 10° flared topside. For this experiment, the 10° tumblehome topside was used. A rendered profile of Model 5613 is shown in Figure 1, and the body plan is shown in Figure 2. A summary of the hull design characteristics for the model are shown in Table 1. Due to the weight of the roll-forcing mechanism, the tested draft was 2.54 cm (1 in) greater than the design draft, making the tested draft 19.7 cm (7.77 in, model scale) and the displacement to 317.5 kg (700 lbs, model scale). The model was fitted with bilge keels of 1.25 m (49.21 in) span (full scale), which were centered at midship with a chord length equal to 1/3 the ship length; no other appendages were included in this test.

Figure 1: Profile of Model 5613

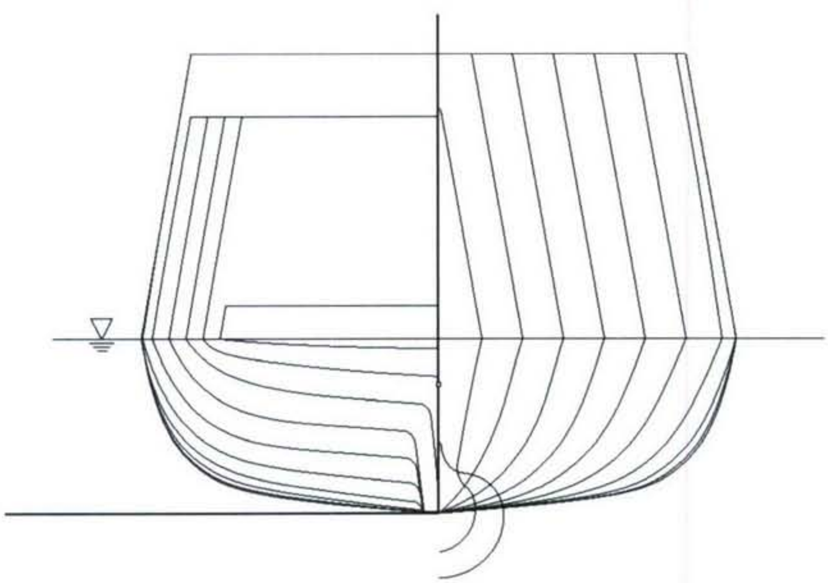

Figure 2: Body Plan of Model 5613

Table 1: Hull Design Characteristics of Model 5613

	Full-Scale (15°C, salt water)		1/32 Model-Scale (20°C, fresh water)	
Lpp	154 m	505 ft	481 cm	15.8 ft (189.6 in)
Beam	18.8 m	61.7 ft	58.8 cm	1.93 ft (23.2 in)
L/B	8.2	8.2	8.2	8.2
Max. Depth	14.5 m	47.6 ft	45.3 cm	1.49 ft (17.8 in)
Max. Freeboard	9.00 m	29.5 ft	28.1 cm	0.92 ft (11.1 in)
Draft	5.50 m	18.0 ft	17.2 cm	0.56 ft (6.77 in)
Displacement	8790 tonnes	8650 LT	261 kg	575 Lbs
LCB (aft of FP)	79.6 m	261 ft	249 cm	8.16 ft
VCB (above BL)	3.26 m	10.7 ft	10.2 cm	0.33 ft (4.01 in)
KM_T	9.74 m	32.0 ft	30.4 cm	1.00 ft (12.0 in)

The radii of gyration and the vertical center of gravity (VCG) of the hull (as tested) were determined by inclining and swinging the underbody from NSWCCD's inertia A-frame apparatus. The VCG was determined to be 24.1 cm (9.5 in) above the keel, with a pitch gyradius of 100.3 cm (39.5 in), roll gyradius of 21 cm (8.25 inches), and a yaw gyradius of 100.6 cm (39.62 in). The longitudinal center of gravity (LCG) was determined to be 10.9 cm (4.3 in) aft of midship. The roll motion was forced at 24.1 cm (9.5 in) above the keel, and 8.1 cm (3.2 in) aft of midship.

Two components of data in this experiment will be affected by the 0.03 m (1.1 in) difference between LCG and the center of rotation, the pitch motion and the yaw moment. Yaw moment will be different because of the difference between LCG and the longitudinal center of rotation for the mechanism. The measured pitch motion will be the same along the centerline of the model, although the actual pitch motion would be slightly different as a result of the 0.03 m (1.1 in) difference between LCG and the center of rotation.

Figure 3(a) shows the model in the zero roll position with the coordinate axes used. All angles (roll, pitch, yaw) are reported relative to the ship at this starting position.

All forces, moments, and accelerations are reported in ship coordinates. Figure 3(b) shows the model in the 50° roll position.

(a) Model in zero roll position. (b) Model in 50° roll position.

Figure 3. Model positions during testing.

EXPERIMENTAL DESCRIPTION

This experiment was conducted in the Deep Water Basin, Towing Carriage No. 2, which is 6.7 m (22 ft) deep, approx. 575 m (1886 ft) long, and 15.5 m (50.96 ft) wide (Figure 4). Maximum carriage speed on Carriage 2 is 10.3 m/s (33.8 ft/s, 20 kts), which is uniform to within 0.01 knots, total variation. Figure 5 shows a schematic of Model 5613 mounted to the carriage, which was the same configuration for both the 2005 and 2006 experiments. The roll/pitch mechanism (Figure 6) allowed the model to roll to a maximum of 50°, while allowing freedom of pitch to 25° in either direction. The section of the model containing the roll/pitch mechanism was separated from the rest of the model and filled with foam to prevent water from entering, while the remaining sections of the model were outfitted with a Lexan cover to keep water out (Figure 7). Figure 8 shows the model with the motor and gearbox assembly inside.

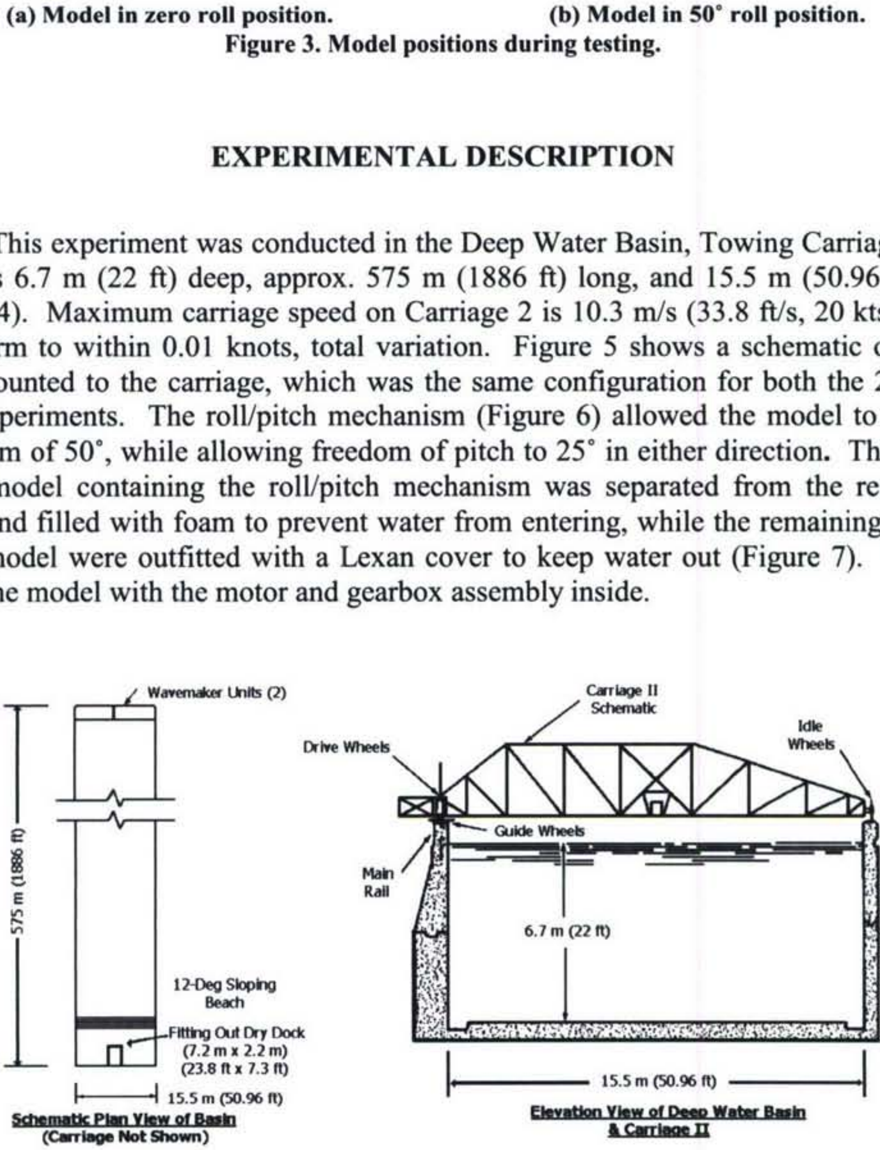

Figure 4: Schematic drawing of the Deep Water Basin, Carriage 2

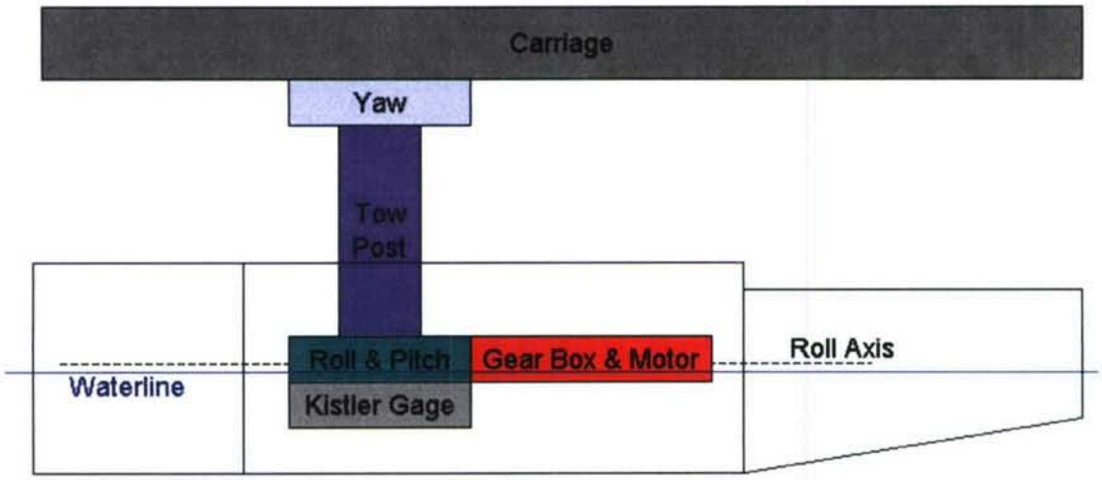

Figure 5: Schematic of model setup.

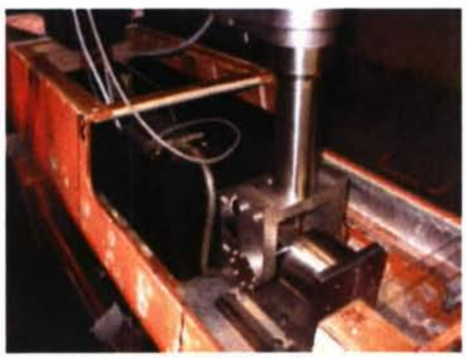

Figure 6: Roll/Pitch Mechanism

Figure 7: Section of Model 5613 with roll and pitch mechanism.

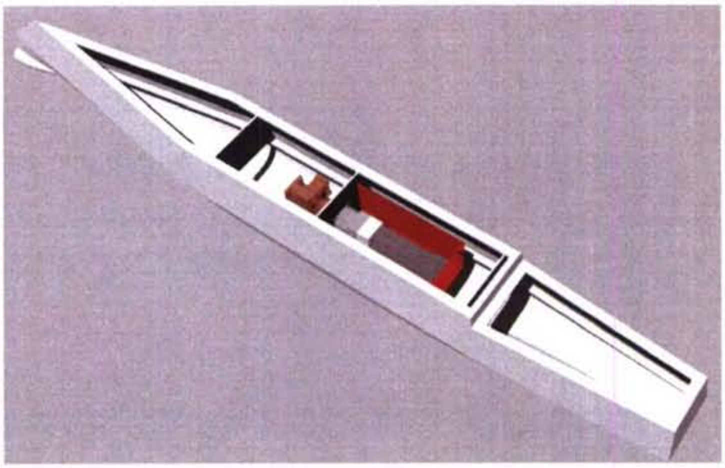

Figure 8: Model 5613 with motor and gearbox inside.

Three-component force and moment measurements were made using a Kistler gage, which was mounted to the model interior underneath the roll/pitch mechanism, as shown in Figure 5. The Kistler gage was used to measure the forces and moments resulting from the constrained motions, including the sway force, the drag force, the roll moment and the yaw moment. The amplitudes and accelerations of the free motions (heave, pitch, and yaw for the free yaw configuration) were measured using a motion package built at NSWCCD. The motion package was mounted inside the hull 88.6 cm (34.9 in) forward of midship and 2.5 cm (0.97 in) above the center of gravity. Vertical acceleration is reported at this point near the bow in model coordinates. Pitch and roll motion values remain the same regardless of location. Standard frame rate (30 fps) video cameras were used to visually document ship motions from multiple views.

Incoming waves were measured using five Senix TS-15 distance sensors (5 sensors/channels), with a capability to measure distances in air from 25 cm (10 in) to 9.1 m (30 ft), to accuracies of 0.1% at 20 Hz. The diagram in Figure 9 shows the locations of the ultrasonic wave height sensors and video camera equipment. The Senix sensors were located 3.05 m (5.5 in) (S1), 3.07 m (121 in) (S2), and 6.51 m (256.5 in) (S3) from the bow of the model. Six additional Senix sensors were located on each side of the model, three on the port and starboard sides, respectively, at 0.46 m (18.25 in) aft of the tow post. These sensors were located 0.15 m (6 in) port (S6) and starboard (S7) of the centerline, 0.03 m (12 in) port (S5) and starboard (S8) of the centerline and 0.6 m (24 in) port (S4) and starboard (S9) of the centerline. Finally, visualization of Model 5613 was captured using standard frame rate (30 fps) video cameras using bow quartering (C2) and stern quartering views (C1).

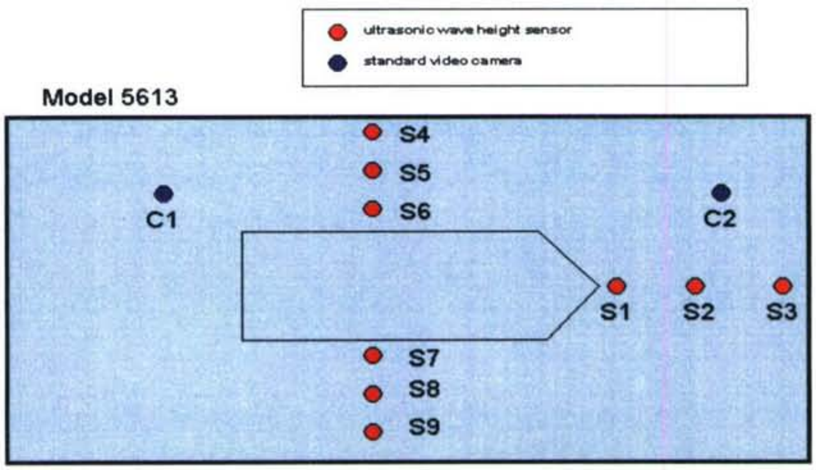

Figure 9: Diagram of ultrasonic wave height sensors and standard video camera equipment

The test conditions included three wave heights, two wavelengths, six roll amplitudes (the model was also tested with no roll), three roll periods, and four carriage speeds (including 0). The model was tested in the fixed yaw condition with bilge keels as the only appendage. Table 2 shows the test matrix with the values of these variables, and Table 3 shows the wavemaker settings used to generate the waves heights and lengths listed in Table 2. Froude number (Fn, $V/\sqrt{gL}$) is a dimensionless number defined as the velocity over the square root of gravity multiplied by the length scale, which is the model length in this case.

Table 2: Test Matrix

Roll Amplitude	Wave Amplitude	Wave Length	Roll Period	Carriage Speed
degrees	cm (in)	m (ft)	s	Fn, (m/s, knots)
0	5.6 (2.2),8.6 (3.4),11.7 (4.6)	4.82 (15.8)	1, 2, 3	0 (0), 0.15 (1.0, 2.0), 0.25 (1.7, 3.3), 0.4 (2.7, 5.3)
5	5.6 (2.2),8.6 (3.4),11.7 (4.6)	4.82 (15.8)	1, 2, 3	0 (0), 0.15 (1.0, 2.0), 0.25 (1.7, 3.3), 0.4 (2.7, 5.3)
10	5.6 (2.2),8.6 (3.4),11.7 (4.6)	4.82 (15.8)	1, 2, 3	0 (0), 0.15 (1.0, 2.0), 0.25 (1.7, 3.3), 0.4 (2.7, 5.3)
20	5.6 (2.2),8.6 (3.4),11.7 (4.6)	4.82 (15.8)	1, 2, 3	0 (0), 0.15 (1.0, 2.0), 0.25 (1.7, 3.3), 0.4 (2.7, 5.3)
30	5.6 (2.2),8.6 (3.4),11.7 (4.6)	4.82 (15.8)	1, 2, 3	0 (0), 0.15 (1.0, 2.0), 0.25 (1.7, 3.3), 0.4 (2.7, 5.3)
45	5.6 (2.2),8.6 (3.4),11.7 (4.6)	4.82 (15.8)	1, 2, 3	0 (0), 0.15 (1.0, 2.0), 0.25 (1.7, 3.3), 0.4 (2.7, 5.3)
50	5.6 (2.2),8.6 (3.4),11.7 (4.6)	4.82 (15.8)	1, 2, 3	0 (0), 0.15 (1.0, 2.0), 0.25 (1.7, 3.3), 0.4 (2.7, 5.3)

Table 3: Wavemaker settings, doors open.

Wave Amplitude	Wave Height	Wave Length	Lip Setting	Blower Setting	Frequency
cm (in)	cm (in)	m (ft)		RPM	Hz
5.59 (2.2)	11.2 (4.4)	4.82 (15.8)	Down	360	0.57
8.64 (3.4)	17.3 (6.8)	4.82 (15.8)	Down	480	0.57
11.68 (4.6)	23.4 (9.2)	4.82 (15.8)	Down	675	0.57

RESULTS

Figure 10 shows a typical time series for the waves encountered by Model 5613 during testing. The top panel shows a wave height of 11.2 m (4.4 in), with a wavelength of 4.82 m (15.8 ft), the middle panel shows a wave height of 17.3 m (6.8 in), with a wavelength of 4.82 m (15.8 ft), and the bottom panel shows a wave height of 23.4 cm (9.2 in), with a wavelength of 4.82 m (15.8 ft).

Figures 11-21 show the forces, moments and motions on the model moving with a Fn of 0.25 (1.7 m/s, 3.3 kts) in waves with a height of 11.2 m (4.4 in) and wavelength of 4.82 m (15.8 ft), for the case of 5° of roll (top panel), 30° of roll (middle panel), and 50° of roll (bottom panel), all with a 2 second period. Figure 11 shows the roll motion (black dashed line) and the sway force (red solid line) of the model. In general, the sway force is in phase with the roll motion, increases with roll amplitude, and is affected very little by the incoming waves, since these are head seas. Figure 12 shows the power spectrum of the sway force, shown as a percentage of the total power, for a model Fn of 0.25 (1.7 m/s, 3.3 kts, model scale) in waves with a height of 11.2 m (4.4 in) and wavelength of 4.82 m (15.8 ft), for the cases from 5° through 45°. The largest percentage of the power from sway is contained at 0.5 Hz, which corresponds to the 2 second roll period. At 5° of roll, there is a small component of power at a frequency of 0.92 Hz, which corresponds to 0.56 Hz, due to the 1.8 second period wave when corrected for model speed.

Figure 13 shows the roll motion (black dashed line) and the drag force (blue solid line). The magnitude of the average drag force increases slightly as the roll amplitude increases. In general, the magnitude of the peak drag forces are greatest for the 45° roll case. Figure 14 shows the power spectrum of drag force, shown as a percentage of the total power, for the a Fn of 0.25 (1.7 m/s, 3.3 kts, model scale) in waves with a height of 11.2 m (4.4 in) and wavelength of 4.82 m (15.8 ft), for the cases from 5° through 45°. The most power over all roll amplitudes is seen at a frequency of 0.92 Hz, which when corrected for speed corresponds to 0.56 Hz, due to the 1.8 second period wave. This plot suggests that the drag force is more affected by the encountered wave than by the roll motion. At larger roll amplitudes (30° and 45°), a smaller percentage of power is evident at the 1 Hz frequency (1 second period), which is half the roll period. This value is the maximum drag that occurs as a larger projected area appears at each half roll period (i.e. roll to port, roll to starboard).

Figure 15 shows the roll motion (black dashed line) and the vertical acceleration (red solid line) of the model, in ship coordinates, at the motion package location (88.6 cm (34.9 in) forward of midship) for three roll amplitudes. At the lower roll angle of 5°, variation in vertical acceleration appears to be mostly due to the encountered waves. For the 30° and 50° cases, it appears that there are added acceleration changes due to the larger roll motion of the model which would be at half the roll period of the model. Figure 16 shows the roll motion (black dashed line) and the vertical acceleration (red solid line) of the model for the same speed and roll period, at the same location, in calm water for roll amplitudes of 5°, 30°, and 50°. There is little change in vertical acceleration at the 5° roll angle, but at 30° and 50°, there are two troughs in the vertical acceleration in one roll period; one for maximum roll to port, one for maximum roll to starboard. These troughs exist mostly because the vertical acceleration is in the model-fixed coordinate system; as the ship rolls to one side, only a portion of gravity is experienced in the model-fixed z direction, with the remainder experienced in the model-fixed y direction. At the maximum roll angle of 30°, the model-fixed y acceleration (in units of g) would be sin(30°), while the z acceleration would be cos(30°) (about 0.87g, as shown in Figure 16). When waves are added, the additional change in vertical acceleration at a different frequency will cause the vertical acceleration to look as it does in Figure 15. Figure 17 shows the power spectrum of vertical acceleration, shown as a percentage of the total power, for the model Fn of 0.25 (1.7 m/s, 3.3 kts, model scale) in waves with a height of 11.2 cm (4.4 in) and wavelength of 4.82 m (15.8 ft), for the cases from 5° through 45°. At the lower roll amplitudes, the most power is seen at a frequency of 0.92 Hz, which when corrected for speed corresponds to 0.56 Hz. At the larger roll amplitudes, a smaller percentage of power is evident at 1 Hz (period of 1 second).

Figure 18 shows the roll motion (black dashed line) and the pitch motion (red solid line) of the model. In this coordinate system, pitch angle is negative when the model is bow up. Again at the lower roll angle of 5°, variation in pitch appears to be mostly due to the encountered waves. As the roll amplitude increases, pitch angle begins to vary with both the encountered wave and the roll angle. Figure 19 shows the power spectrum, shown as a percentage of the total power, for a Fn of 0.25 (1.7 m/s, 3.3 kts, model scale) in waves with a height of 11.2 cm (4.4 in) and wavelength of 4.82 m (15.8 ft), for the cases from 5° through 45°. The peak frequencies in this signal are at 0.5 Hz, which is due to the 2 second roll period, and about 0.92 Hz. When corrected for speed, this frequency corresponds to 0.56 Hz, which suggests that most of the pitch motion is due to the wave frequency, with a lesser amount being due to the roll motion of the ship. As the roll amplitude increases, the percentage of total power due to the roll motion increases.

Figure 20 shows the roll motion (black dashed line) and the forced roll moment (red solid line) of the model at the center of rotation. The roll moment is in phase with the roll motion, and the amplitude of the roll moment increases with increased roll amplitude. Figure 21 shows the roll motion (black dashed line) and the yaw moment (red solid line) of the model at the center of rotation. Roll motion and yaw moment are out of phase, and the amplitude of the yaw moment increased with increased roll motion.

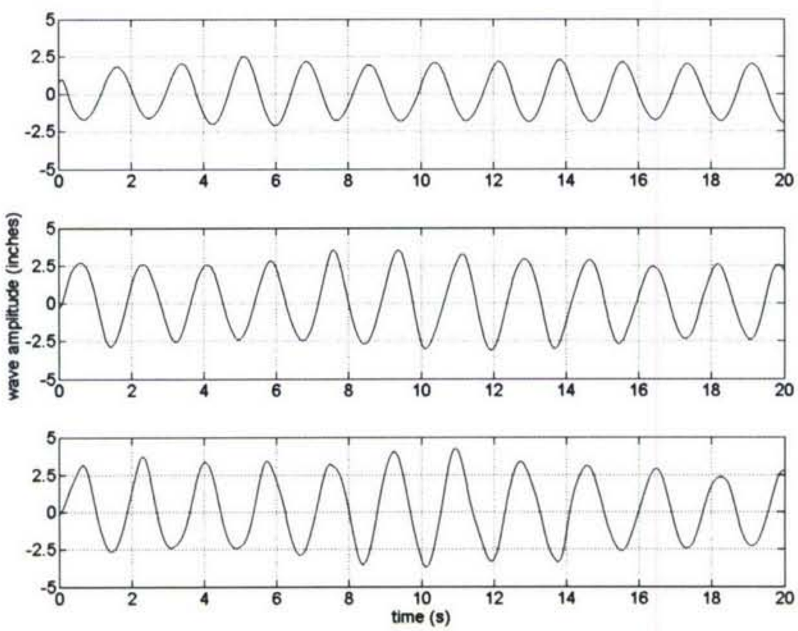

Figure 10. Typical Wave Time Series During Testing. Top panel shows a wave height of 11.17 cm (4.4 in), λ=15.8 ft, middle panel shows a wave height of 17.27 cm (6.8 in), λ=4.82 m (15.8 ft), and bottom panel shows a wave height of 23.37 cm (9.2 in), λ=4.82 m (15.8 ft).

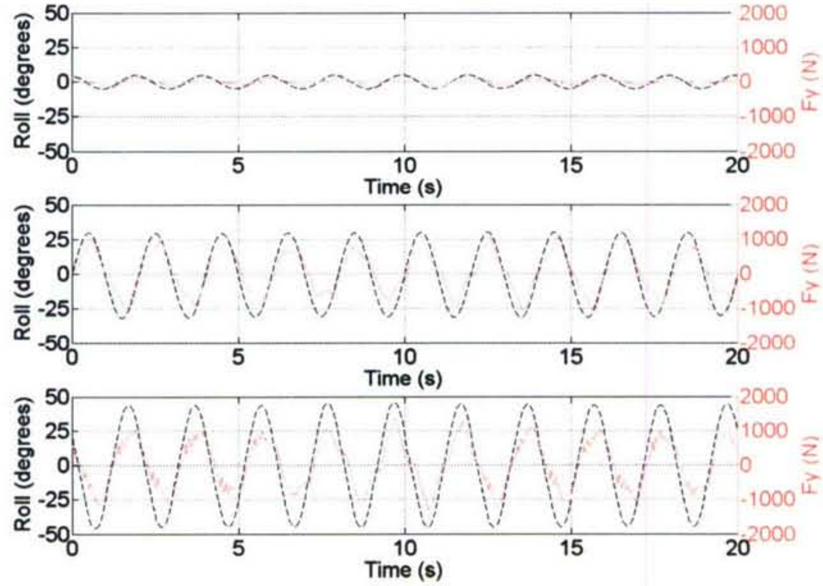

Figure 11. Sway force on model for 5° roll (top panel), 30° roll (middle panel), and 45° roll (bottom panel) for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts) for wave height of 11.17 cm (4.4 in), λ=4.82 m (15.8 ft).

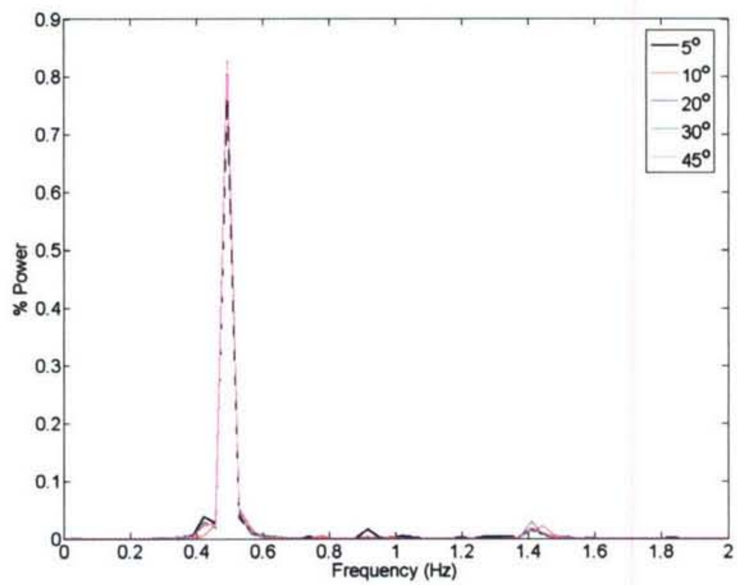

Figure 12. Percent power contained in sway for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts) for wave height of 11.17 cm (4.4 in), λ =4.82 m (15.8 ft).

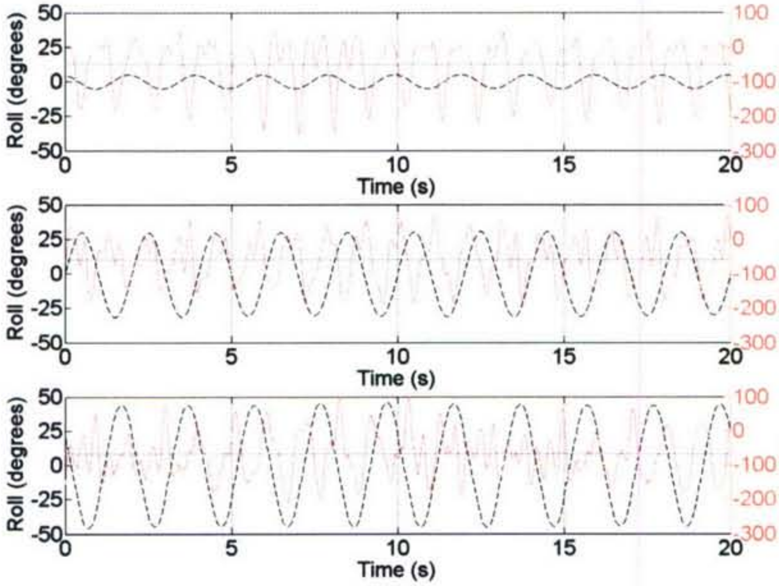

Figure 13. Drag force on model for 5° roll (top panel), 30° roll (middle panel), and 45° roll (bottom panel) for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts) for wave height of 11.17 cm (4.4 in), λ=4.82 m (15.8 ft).

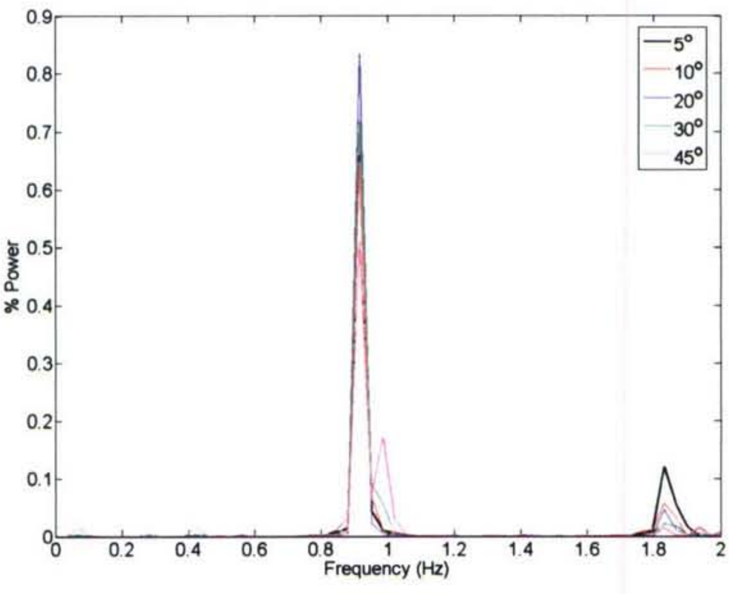

Figure 14. Percent power contained in drag for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts) for wave height of 11.17 cm (4.4 in), λ=4.82 m (15.8 ft).

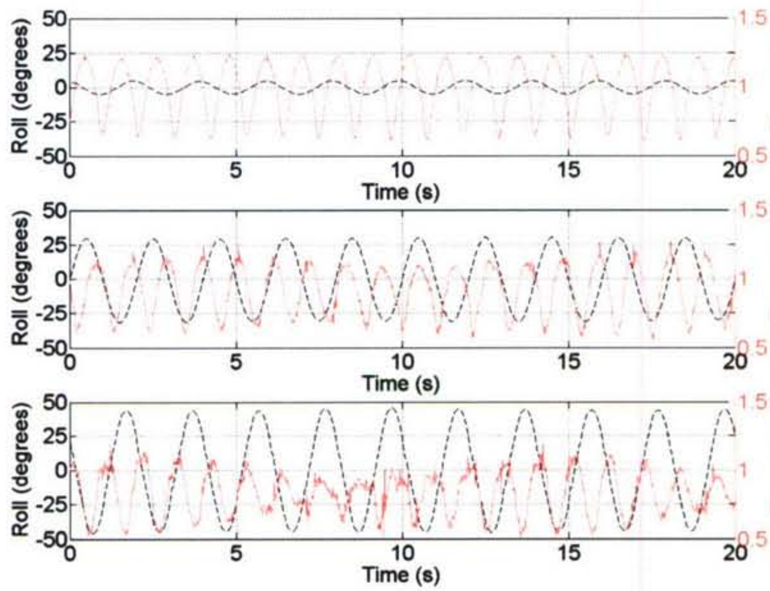

Figure 15. Vertical acceleration of model for 5° roll (top panel), 30° roll (middle panel), and 45° roll (bottom panel) for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts) for wave height of 11.17 cm (4.4 in), λ=4.82 m (15.8 ft).

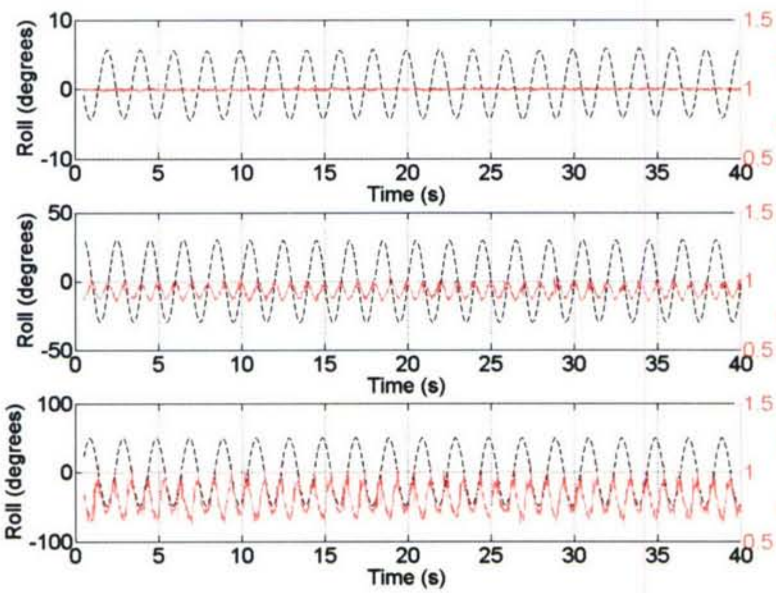

Figure 16. Vertical acceleration of model for 5° roll (top panel), 30° roll (middle panel), and 50° roll (bottom panel) for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts) in calm water.

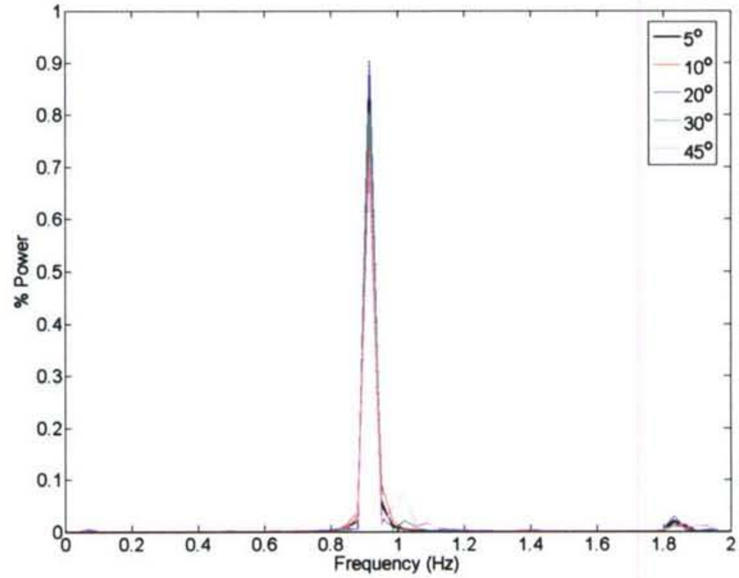

Figure 17. Percent power contained in heave acceleration for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts) for wave height of 11.17 cm (4.4 in), λ=4.82 m (15.8 ft).

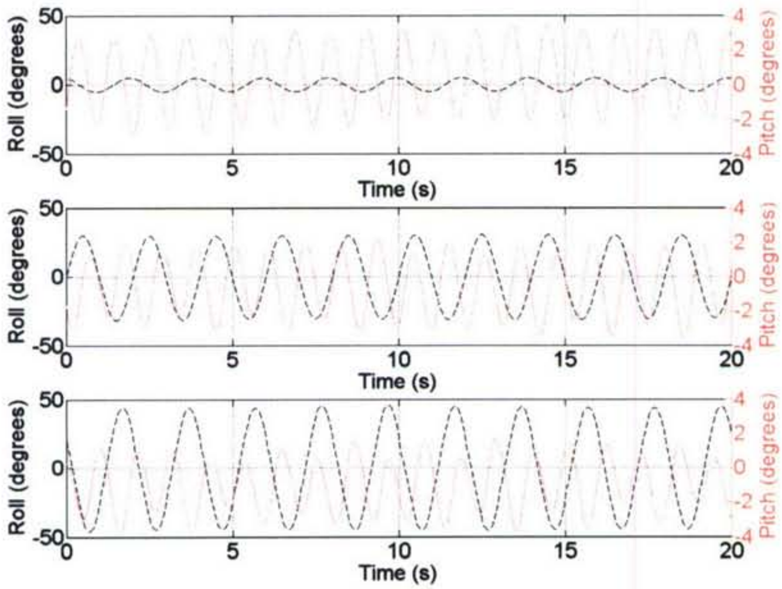

Figure 18. Pitch of model for 5° roll (top panel), 30° roll (middle panel), and 45° roll (bottom panel) for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts) for wave height of 11.17 cm (4.4 in), λ=4.82 m (15.8 ft).

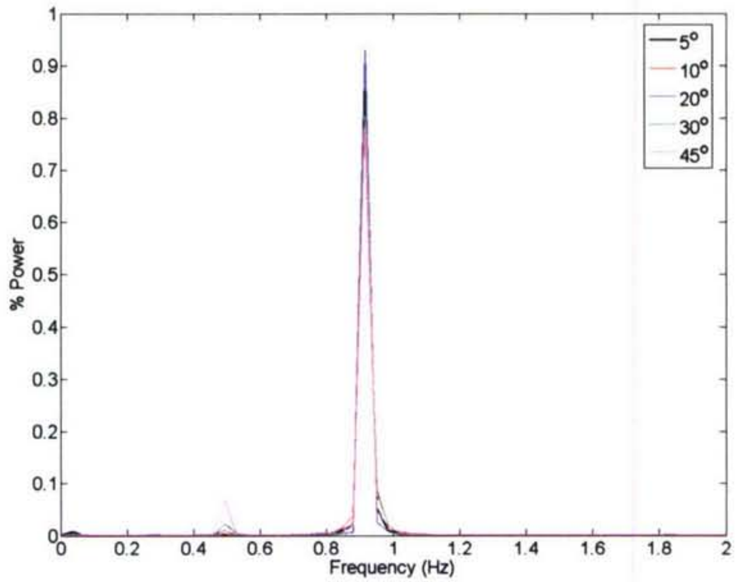

Figure 19. Percent power contained in pitch for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts) for wave height of 11.17 cm (4.4 in), λ=4.82 m (15.8 ft).

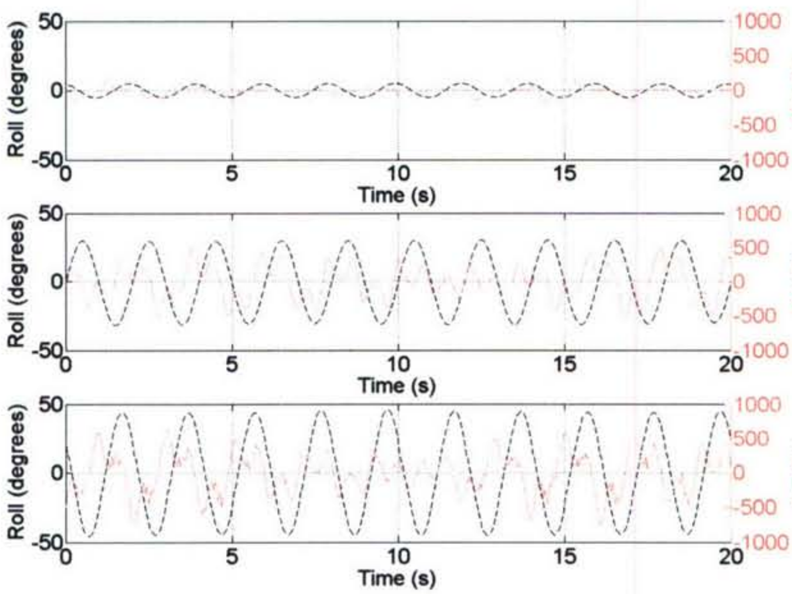

Figure 20. Roll moment for model for 5° roll (top panel), 30° roll (middle panel), and 45° roll (bottom panel) for a 2 second roll period at Fn of 0.25 1.7 m/s, 3.3 kts) for wave height of 11.17 cm (4.4 in), λ=4.82 m (15.8 ft).

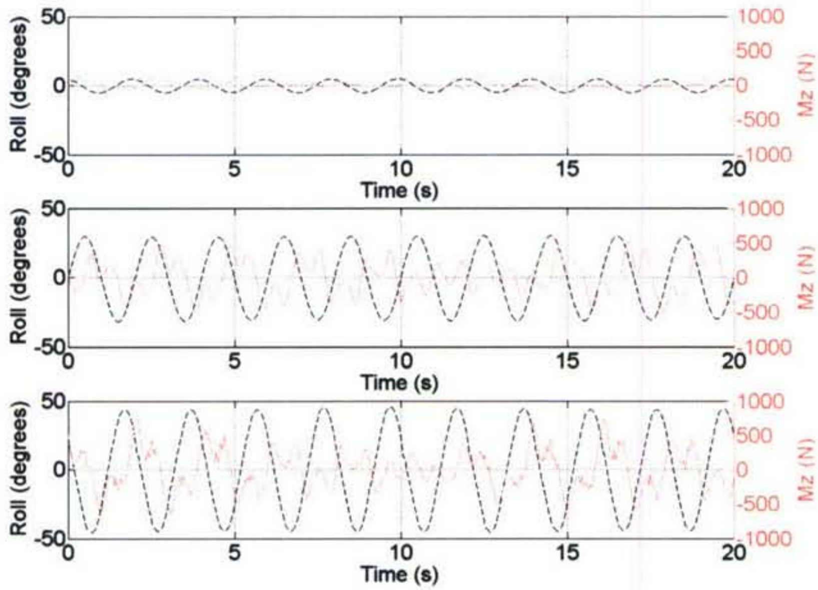

Figure 21. Yaw moment for model for 5° roll (top panel), 30° roll (middle panel), and 45° roll (bottom panel) for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts) for wave height of 11.17 cm (4.4 in), λ=4.82 m (15.8 ft).

CONCLUSIONS

In general, the sway force is in phase with the roll motion, and increases with roll amplitude. It appears that the incoming waves have only a slight effect on the sway force, most likely because they were head seas. The drag force increases with increased roll amplitude and wave height, but appears to be more affected by the encountered wave than by the amplitude of induced roll motion. At smaller roll angles, variation in pitch appears to be mostly due to the encountered waves, however, as the roll amplitude increases, pitch angle begins to vary with both the encountered wave and the roll angle. Roll motion and yaw moment are out of phase, and the amplitude of the yaw moment increases with increased roll motion.

This experiment focused on the forces and moments experienced by a surface combatant hull due to large amplitude motions in head seas, providing for an extensive database of forces and moments from roll amplitudes extending up through 50 degrees, which are useful in verifying model predictions for large roll amplitudes. This report includes representative data from the experiment, time series are available for all conditions upon request.

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